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A medium-depth ice core drill

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Abstract: Taking as a model the Alfred Wegener Institute medium depth ice core drill, we have developed a drill capable of retrieving ice cores to depths of around 150–200 m. At a total system weight of 340 kg, including drill, winch, cable, tower and generator, the system is easily transported by Twin Otter aircraft. Two identical copies of the drill system were produced, and used to drill successfully at eleven locations in both the Arctic and the Antarctic. Ice conditions experienced during drilling ranged from cold Antarctic plateau sites to Arctic sites close to melting, and also blue, bubble-free ice.

1. Introduction

Following the loss of its earlier Institute of Low Temperature Science ILTS-130 ice core drill, the British Antarctic Survey (BAS) needed to source a new drill capable of achieving moderate depth ice cores. Design criteria included a relatively lightweight system easily transported by Twin Otter aircraft, that could be operated from a small petrol generator, yet capable of depths of up to about 200 m. This depth includes ice that is often found to be brittle, so consideration had to given to reducing any factors that may cause fractures to the ice during drilling. Planned analyses on the ice suggested a core diameter of around 100 mm was required.

Since BAS had little expertise in designing a new drill, our preferred route was to copy an existing drill, and adapt it to fit our particular requirements. We were fortunate in finding a suitable design with a successful track record in the medium-depth drills produced by Alfred-Wegener-Institute (AWI), and advice from the AWI engineers was particularly useful in the early design stage. In fact, the drill we finally produced is very similar to the AWI drill, which in turn has many features of earlier Swiss designs (Rufli *et al.*, 1976; Schwander and Rufli, 1988). The main design changes included: lighter weight winch system; increase in core diameter to 106 mm for recovery of greater ice volume; splines on inner surface of outer barrel manufactured separately and fastened to outer barrel, avoiding the high cost of speciality drawing of an aluminium tube with integral splines through a custom mandrel favoured by AWI; inclusion of a hammer action in head for applying a shock to the head during difficult core breaking.

The final design drawings for the drill were produced at BAS, and manufacture subcontracted to a small local engineering company. Two identical copies of the drill were produced: one for BAS operations, and one for the University of Utrecht Institute for Marine and Atmospheric Research (IMAU). The winch and tower system were manufactured by MacArtney AS[1] to our design criteria; again, two identical systems were produced for BAS and IMAU. The total weight of the drilling system, including winch, cable, tower, drill and generator is 340 kg.

2. Drill description

The drill adopts the standard layout for dry-hole drills of an upper anti-torque section above a motor/gear section driving an inner barrel inside a fixed outer barrel. A barrel release section allows the inner barrel to be withdrawn from the outer barrel for removing the chippings and core from the top end of the barrel. Figure 1 shows the general layout

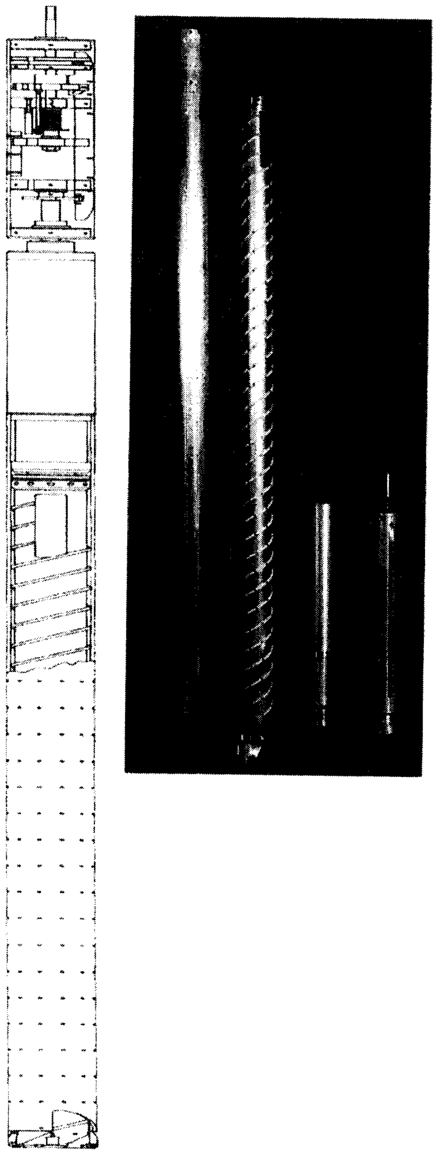

Fig. 1. General layout of the drill (schematic diagram is foreshortened for clarity).

[1] MacArtney A/S, Esbjerg, Denmark; http://www.macartney.com

of the drill, which is overall 4.6 m in length, and weighs 80 kg. Core diameter is 106 mm, while the hole diameter is 143 mm. We power the whole drill and winch system with a single standard Honda EC4000 3.4 kW, 230 V, single phase, petrol generator (weight 60 kg).

The anti-torque section (Fig. 2) uses blades to grip the borehole walls (similar to the system described by Schwander and Rufli (1988)), rather than the more common spring type anti-torque used on most ice core drills. Six sharp steel blades are located in three skates mounted at 120° centres longitudinally along the section. Allowance is made for the distance the blade protrudes from the skate to be adjusted to accommodate differing firn hardness. The design allows the skates and blades to be withdrawn into the housing under the weight of the drill hanging from the cable. Once the load on the cable reduces, as the drill reaches the base of the borehole, a spring on the central shaft acts to push out the upper end of the skate forcing the blades onto the borehole wall. As the drill begins to turn, the torque reaction causes a cam, located on the lower anti-torque shaft, to force out the lower end of the skate. With this arrangement, the greater the torque transmitted to the cam, the higher the force of the lower skate and blade against the borehole wall. This anti-torque arrangement appears successful, and we have not experienced rotation of the entire drill, or damage to the cable, despite having no slip-ring assembly between the

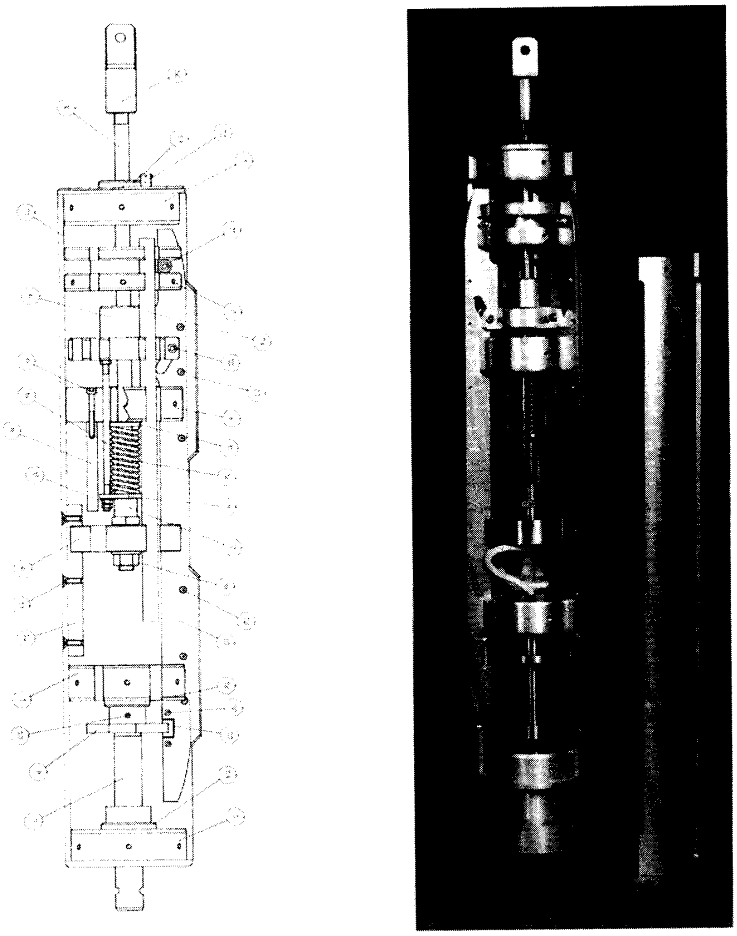

Fig. 2. Anti-torque section (blades shown in drawing, but missing from image).

cable and the drill. However, we cannot yet determine whether this system is more or less successful than the common spring-type anti-torque system. Once a drilling run is complete, and the drill is lifted, the weight of the drill on the cable pulls the skates and blades back into the housing for transit up the borehole. This section also includes a small hammer device for difficult core breaks. Located on the same shaft that drives the mechanism for withdrawing the skates, the heavy stainless steel hammer weight has a short travel of about 100 mm against the skate spring before it hits against three rods, transmitting the shock via the housing to the shaft connected to the inner barrel, and on to the drill head.

The motor/gear section houses a two-pole, permanent magnet, 180 V DC motor (model DPM30X2, manufactured by SEM Ltd[2]) producing 750 Watts at 2500 rpm, with a maximum continuous stall torque of 1.4 Nm (peak stall torque 5 Nm). The overall dimensions of this motor are 115 mm diameter, 276 mm length, with a weight of 11 kg. The 14 mm diameter output shaft drives the inner barrel through a Cyclo[3] gear reducer (model XFCG 208-21) with a reduction ratio of 21 : 1, and dimensions 110 mm diameter, 155 mm length, and weight 4.5 kg. This reduction ratio implies a maximum drill head rotation speed of 120 rpm. Motor speed control is by a DC drive (Eurotherm[4], type 508): this simple drive is designed for operating on a single phase AC supply, producing a variable (to 180 V) DC output, and rated at up to 12 A full load current. In practice, the

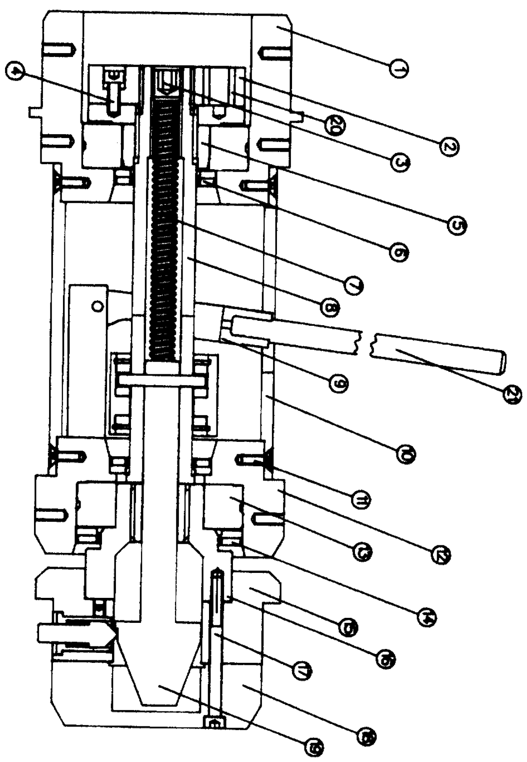

Fig. 3. Barrel release section.

[2] SEM Ltd, Orpington, UK; http://www.sem.co.uk
[3] CYCLO GmbH, now part of the Sumitomo group, http://www.smcyceuro.com
[4] Eurotherm, Littlehampton, UK; http://www.eurotherm.co.uk

motor can be driven as low as 30 V, or 20 rpm at the drill head.

The barrel release section (Fig. 3) houses the mechanism for withdrawing three pins that lock the inner barrel to the main drive shaft, and is similar to the coupling described by (Rufli *et al.*, 1976). A three-sided cone is drawn back against a spring, allowing the pins to disengage from the crown of the barrel under the force of individual springs. Locking the barrel onto the drive shaft is achieved when the cone is released forcing the pins out. Positive confirmation that the barrel is locked onto the drive shaft comes from the position of the lever operating the release cone.

The inner and outer barrels are both made from drawn aluminium alloy tube (grade HT30TF). The outer barrel has a series of grooves ~15 mm wide, between ~25 mm wide splines running longitudinally along the inner surface of the barrel to aid chip transport (Fig. 4 shows some of the detail). Our intention had been to extrude the outer barrel to this profile, but the cost of producing the mandrel and custom drawing the aluminium tube was well above budget. Instead, we purchased two telescoping aluminium tubes, and cut the smaller tube into short sections of the splines, then bonded them into place with acrylic adhesive transfer tape to the inside of the outer barrel, and finally, secured them with screws. The inner barrel has three parallel spiral wound acetal flights, which were machined to the final pitch, but at a slightly smaller diameter. These were then bonded to the inner barrel using acrylic adhesive transfer tape, and screwed into place. Since the screws protruded slightly into the inside of the barrel, we finally machined the inside to a smooth bore. To achieve a tight fit to the outer barrel (to reduce vibration of the barrels during drilling), the flights were machined to fit the internal diameter of the outer barrel.

The drill head (Fig. 5) is equipped with three circular cutting teeth, three sprung

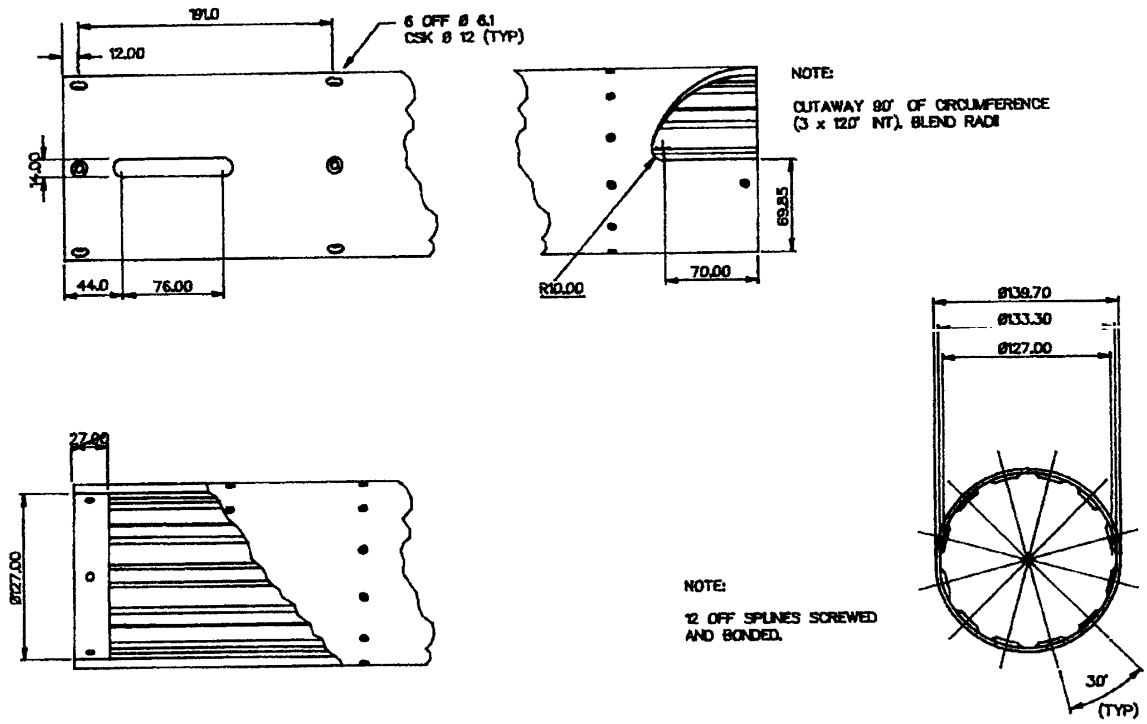

Fig. 4. Detail of splines on outer barrel.

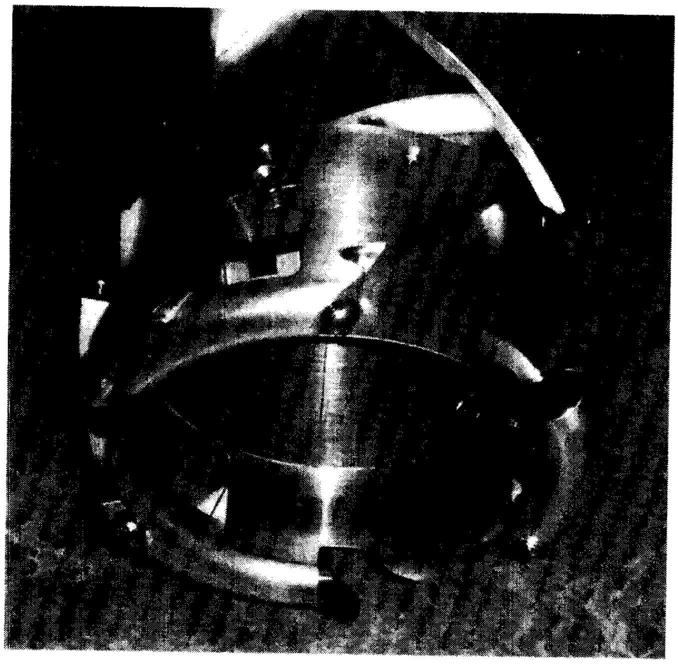

Fig. 5. Drill head.

core-catchers, and three small tool bits for enlarging the hole diameter (in practice not needed at the depths so far reached), and is very close to the original AWI design. The rounded cutters were designed in an attempt to improve the quality of the core, by reducing radial stress cracking, but may suffer from a less efficient cutting action. Both cutters and core-catchers were machined from grade BS4659 : 1971 : B01 oil-hardening tool steel. We originally chose not to harden the catchers and teeth after manufacture to ease sharpening in the field, but subsequent experience has shown that hardening the cutters improves cutter efficiency and core quality. Drill pitch setting is simply achieved by varying the number of washers on screws on the lower, rounded, face of the head annulus, behind each cutter.

3. Winch system

The winch system has a capacity of 300 m of 6.5 mm diameter cable. It is built on an aluminium base 1.1×0.65 m. Sledge-runners on the underside of the base make manoeuvring in soft snow by hand easier, and the runners are matched to the width of the double ramp beams attached to the doorway of our Twin Otter aircraft to assist loading.

A standard 1.1 kW, three phase 230/400 VAC gear-motor (Bonfiglioli Riduttori[5] type C202P-7.1-SP 3 phase motor), drives via a chain pulley through a gear reducer (Bonfiglioli Riduttori type TA45.50D) to the drum shaft. Motor speed is controlled via a frequency convertor motor controller (Danfoss type VLT 2030), with a maximum motor speed of 2800 rpm at 100 Hz (392 rpm on the output shaft of the gear-motor), and a specified minimum of 25 Hz (though in practice we use a minimum of 12 Hz, and have not experienced problems). With the standard chain drive gearing of 1.25 : 1, and the drum-

[5] Bonfiglioli Group; http://www.bonfiglioli.it

shaft gearing of 25 : 1, the maximum drum speed at 100 Hz is 12.5 rpm, equating to 13.8 m cable per minute. Design pull on the cable is 6360 N at 50 Hz on an empty drum (for core-breaking at full depth), reducing to 2500 N on a full drum at 100 Hz (at maximum winching speed). Functional tests in a cold room at −20°C showed that the winch maintained a pull in excess of 800 kg at 50 Hz (with an empty drum) for short periods, exceeding the design criteria, and in practice sufficient for core breaking. Winch system weight, without cable, is 150 kg.

Dynamic braking of the winch is achieved by effectively turning the motor into a generator, and dumping the load across a large resistor. A motor brake is built onto the gear-motor which will stop the motor and drum instantly for emergency breaking of the winch, with panic stop switches mounted on both the controller and the drum support; this is a safety aspect rather than an operational brake. Finally, the winch is built with a facility for hand cranking the drum for drill recovery, should failure of the winch motor occur during winding. A ratchet assembly can be engaged to assist manual winding.

The cable used is a 6.35 mm diameter Rochester[6] type 4-H-250A cable constructed with four 22 AWG conductors, weighing 15.9 kg per 100 m. The minimum breaking strain of 25.8 kN, and the working load is specified as 10.3 kN, above the maximum power of the winch. DC power to the drill is taken by doubling up the conductors; we do not use the cable outer case as the return. The power passes through the axis of the drum via a 4-conductor slip ring assembly (Focal Technologies[7], Model 180).

The cable is led from the drum to a sheave wheel on top of a fixed 5.3 m long aluminium tower. The tower is attached at the lower end to an articulated ball-joint on the base plate of the winch, immediately in front of the drum. The mast design is not intended to tilt, and is guyed from the upper end. The location of the mast foot on the winch base means the borehole is situated close to the drum, requiring a small cut-away in the winch base. A load cell, and optical encoder, provide the operator with an indication of the load on the cable, cable length paid out, and the rate of ascent/descent.

4. Experience of the drill system in the field

The two identical drill systems produced have been used in a wide range of field situations (Table 1), including warm Arctic glaciers close to melting temperature, cold polar firn and ice, and bubble-free blue ice. Generally, in all conditions the drill system has worked well. In the glacier ice close to melting, we experienced sticking of the chippings on the inner barrel flights, making chip transport problematic, and providing the limit on depth as we approached water-soaked ice. It is possible we could overcome this limitation with a plastic coating on the barrels to reduce sticking.

As built, the inner barrel is a tight fit in the outer barrel; this was intended to avoid vibration damage to the more brittle cores. The power drawn by the motor with the barrels freely rotating (*i.e.* not under cutting load) is 0.6 A at 180 V, reflecting the friction of the inner barrel flights. During drilling, we commonly ran the motor at 120 to 140 V (a head rotation speed of about 80 to 95 rpm). Normal cutting power was usually in the

[6] Rochester Corporation, http://www.rochestercables.com
[7] Focal Technologies, Dartmouth, Canada; http://www.focaltech.ns.ca

Table 1. Successful drilling operations using this drill design.

Site	Location and altitude	10 m temperature (°C)	Total depth (m)	Depth of firn layer[1] (m)
BAS drill				
Berkner Island, Jan. 1995	S78°18.4′ W046°16.4′ 717 m asl	−24.1°	152	65
EPICA Fuel Depot, Dronning Maud Land, Jan. 1998	S77°02.4′ W010°30.1′ 2176 m asl	−37.7°	123	74
IMAU[2] drill				
Mårmaglaciären, Sweden, April 1997	N68°05′ E018°41′	−0.5°	2×28	5
Lomonosovfonna, Svalbard, May 1997	N78°52.9′ E017°12.5′ 1230 m asl	−2.2°	120	18
Scharffenbergbotnen (blue ice), Dec. 1997	S74°20′ W011°05′ 1216 m asl	−22.8°	85	0
Scharffenbergbotnen (blue ice), Dec. 1997	S74°21′ W011°02′ 1173 m asl	−18.8°	52	8
Camp Maudheimvidda Dronning Maud Land, Dec. 1997	S73°04′ W013°05 363 m asl	−17.8°	2×105	51
Camp Victoria, Dronning Maud Land, Jan. 1998	S76°00′ W008°02′ 2399 m asl	−38.7°	137	72
Lomonosovfonna, Svalbard, May 2000	N78°52.9′ E017°12.5′ 1230 m asl	−2.2°	60	15
EPICA S20, Dronning Maud Land Jan. 2001	S70°14.5′ E004°48.7′ 48 m asl	−23.0°	100	60
EPICA, Site M, Dronning Maud Land Jan. 2001	S75°00.0′ E015°00.1′ 3457 m asl	−47°	160	100

[1] Depth of firn layer given as from a drillers perspective, and may not be true point of pore close-off.

[2] IMAU: Institute for Marine and Atmospheric Research, University of Utrecht, The Netherlands.

range 1.8 to 2.5 A in shallow firn, rising to 2.5 to 3.5 A in ice. Towards the end of the cutting run, as the barrel became filled with core and chippings, the current would rise above 4 A, and the motor often stall (the motor driver has a sensitive stall detection circuit that cuts the motor power when current rises even momentarily above a preset limit), a clear indication that the barrel was full and the run finished. Cutter pitch was set at about 2.5 mm, using the screws/washers on the drill-head. At 95 rpm, this would suggest a drilling time of a little under 3.5 min for a 950 mm core length, which was about in line with the drilling times experienced.

The anti-torque section appears to work well, with no indication of cable damage from rotation of the drill in the hole, despite the absence of a slip-ring assembly between the cable and the drill. This system has the disadvantage that in the upper few metres of firn, wider blades are needed to counter the drilling torque. Below about 10 m, the blades can be changed for narrower blades, which then suffice for all further drilling.

In the firn, core lengths of 950–1100 mm were normal, while in the ice, lengths were reduced to around 850 mm as more of the drill chamber was taken up with chippings. Core quality was reasonable, with little damage to the cores at the Antarctic sites until depths in excess of about 135 m. Below this depth, some runs produced cores in several pieces, mostly broken horizontally across the core, but with occasional longitudinal slivers caused by the core-catchers during breaking. Experimenting with the cutting bits suggested that core quality was improved by better hardening and more regular sharpening of the bits. It is not clear that the rounded design of the core bits led to any significant improvement in the ice core quality. The small tools on the upper part of the head for widening the hole were not used.

Core breaking was usually easy, with very few difficult breaks. More common, particularly in the firn, were grooves in the lower section of the core as the core-catchers were dragged up the core before it finally broke away from the base. As supplied, the winch power (at up to 8000 N) for core breaking was clearly adequate. Both systems were subsequently modified by changing the chain drive cogs to give slightly faster winching speeds (approximately 20% faster) at the expense of the power available for core breaking.

Acknowledgments

We were fortunate to receive a great deal of help from Cord Drücker of the Alfred Wegener Institute in the design of this drill. Roderik van de Wal provided the details of the drilling experience with the version of the drill produced for IMAU.

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